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Engineering Note

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Project: DZERO Solenoid Energization, Controls, Interlocks and Quench protection
Doc. No: H970729A

Subject: Solenoid Charging Voltage Limiter

Introduction to problem -- The DZERO central tracking superconducting solenoid is powered by a Power Energy Industry (PEI), 150 kW power supply which is configured to provide up to 5000 Amps of current at up to 15 Volts. In order to ensure a stabile magnetic field, the power supply is operated in the "current regulated" mode (as opposed to voltage regulated mode). The magnetic field produced by the solenoid is proportional to the current through the solenoid. The advantage of using the current regulated mode of the power supply is that the solenoid current is always constant regardless of slight variations in circuit resistance. Circuit resistance may vary slightly due to temperature changes of the approximately 300 feet (150' per conductor) of water cooled bus and bus interconnections in the system. A disadvantage of operating the power supply in the current regulated mode is the inability to "charge" the solenoid at a controlled rate.

For example, if the power supply was initially "on" but delivering zero current to the solenoid; and was then commanded to deliver 5000 Amps; being current regulated, it would attempt to deliver 5000 Amps by forcing its output to maximum voltage instantly -- in this case, 15 Volts. The rate at which the solenoid charges - the change of current per change of time -- is limited only by the resistance, capacitance and inductance of the solenoid/bus circuit. Unfortunately, if the solenoid is charged at too high of a rate, it will quench.

Test of the solenoid during charging have revealed the following data:[1]

Magnet Terminal Charging Voltage	Current at Which Quench Occurs
1.3 V	No Quench to full field (4800 A)
2.5 V	No Quench to full field (4800 A)
6.25 V	4500 A
9.4 V	3700 A

Thus it is obvious that we need to limit the voltage delivered by the power supply during charging; while allowing current regulation to control the power supply during steady state operation.

Introduction to solution -- We have chosen to use a modification to the PEI regulator that allows us to provide an external "maximum voltage" reference signal to the solenoid power supply[2]. This signal which will be supplied by the operator, via the control system, will effectively "clamp" the output of the solenoid power supply. Using the control system software, we can either provide a fixed voltage limit, or we can change the voltage limit during charging. By changing the voltage during charging, we can charge the solenoid in minimum time. For example, we can utilize a higher voltage while the solenoid current is still low, and gradually lower the voltage as higher currents are approached. One suggestion by R. Smith[3] is to set the charging voltage limit to 10V until the solenoid reaches 2500A, then reduce the charging voltage limit to 6V until 3750A is reached, then 2.5V until

[1]Memo, Smith to Hance, 5/21/97, Subject RE: Solenoid Charging Rate

[2]R. Hance Engineering note H970528A "Controlling the Solenoid Power Supply Regulation During Charge" - Initial conceptual design document.

[3]Memo, Smith to Hance, 5/21/97, Subject RE: Solenoid Charging Rate

4800A is reached. R. Smith provides the observation that a steady 2.5V charging voltage would require 16 minutes to achieve full charge whereas the schedule described above will charge the solenoid in 7.3 minutes.

Implementation of solution -- An operational amplifier circuit was added to the PEI current-voltage regulator module. The circuit consists of two op amps in a single package, with assorted resistors and capacitors, assembled on a small piece of perforated phenolic and affixed to the regulator module[4].

The modification essentially works as follows: Regardless of whether voltage or current regulation is used, the PEI regulator controls its output by controlling the firing angle of its silicon controlled rectifiers. The power supply's output voltage and current are monitored by the regulator and whichever mode is selected controls the SCR firing angles. The regulator continuously adjusts the SCR firing angles to maintain the desired output. The new voltage limiter circuit works in parallel with the regulator. It compares the power supply output voltage to the externally supplied "limit voltage". If the output voltage tends to exceed the "limit voltage" then the voltage limiter circuit clamps the regulator output effectively retarding the SCR firing angles such that the output voltage and "limit voltage" will equalize. The "clamp" is done in such a way that the normal regulator prevails as long as the output voltage is below the limit; and the voltage limiter is only able to prevent the output voltage from exceeding the externally supplied limit.

The design is intended to be "fail safe". If the cable from the control system which provides the voltage limit signal opens or short circuits, then the voltage limiter circuitry will clamp the power supply output to zero volts.

Implementation considerations -- Since the voltage is sampled by the regulator at the power supply output instead of directly at the solenoid terminals, the voltage drop across the 300' of bus and current consumption by the dump resistor must be considered. This will be factored in by the programmable logic controller (PLC) that controls the power supply. Initially, the operator will use a very simple interface. He will remotely control the power supply via the distributed manufacturing and control software (DMACS) which will allow him to designate a target current and a charging voltage limit. DMACS will send the information to the PLC which will scale it and apply it to the power supply. If we later decide that a more complex charging profile is desired (as discussed above), then the modifications will be made to the PLC function to implement this feature.

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[4]The details of the modification/addition to the regulator are shown on the "power supply" schematic which is sheet-7 of the energization system drawings 3823-111-ED-330052 (14 sheets). These drawings are maintained in the DZERO drawing files and on the internet at http://d0sgi0.fnal.gov/~hance/solenoid. The details of the PEI regulator are shown on a PEI schematic which also has a Fermilab drawing number of 6005-ED-172208 and is maintained by the Power Supply Section of the Electrical Support Group of the Particle Physics Division.